An approach to increase the speed of Optical Coherence Tomography using a Virtually Imaged Phased Array

H. Sudkamp, H. Y. Lee, G. Hüttmann and A. K. Ellerbee

Abstract–A novel technique to increase the imaging speed of Optical Coherence Tomography is presented. Data from several lateral points are simultaneously acquired by integrating a virtually imaged phased array (VIPA) into the sample arm. However, the increase in points measured simultaneously comes at the cost of imaging depth.

At an equivalent A-scan rate of 900kHz, we resolved nine lateral points and got an almost equal OCT signal across the whole imaging depth of 0.66 mm.

I. INTRODUCTION

Optical Coherence Tomography (OCT) is a fast imaging technology mainly used in ophthalmology, cardiology and dermatology. In the last several years, much effort has been made to increase the speed, resolution and sensitivity of OCT.

With the increase in speed, for example due to switching from Time Domain OCT to Fourier Domain OCT, new applications became possible (e.g. real-time volumetric measurement) and motion artifacts could be reduced.

Currently, scanning speed poses an additional limit to the imaging speed. When limiting the field of view to a single point, extremely fast measurements are possible. One example is the real-time measurement of the dynamics of laser ablation [1].

Due to the speed currently achievable, imaging of fast processes is limited to a small field of view or even a single point. Higher imaging speed and faster scanning would allow measuring those processes with more lateral points at higher resolutions.

Several groups work on increasing the speed of OCT. For Spectral Domain OCT, the imaging speed is mainly limited by the speed of the camera in the spectrometer. With faster cameras available, the speed of Spectral Domain-OCT was increased in the last years to more than 300 kHz [2].

For swept source OCT (SS-OCT), the limiting factor is the sweep rate of the light source. Fast sweepable laser sources suitable for OCT have been developed by several groups, including [1], [3] and [4]. The VCSEL source shown in [3] is especially interesting, since it offers an imaging depth in the regime of several centimeters to more than one meter in addition to a high sweep rate [5]. Ultimately, the digitizer is mentioned as a limiting factor for these light sources. There are also several fast sweepable light sources for OCT with sweep rates of 100 kHz that are commercially available.

Different from many other groups, our approach increases the speed of the image acquisition without changing the light source, but at the cost of imaging depth.

We added an optical element into the sample arm of an SS-OCT system, which distributes different sets of wavelengths spanning the whole bandwidth of the spectrum emitted by the source to different angles and ultimately lateral points. In order to maintain the depth resolution of a standard OCT system, each lateral point needs to be illuminated by wavelengths across the whole spectral bandwidth.

Most efforts to speed up focus only on increasing the sweep rate of the light source. Our approach of interleaved OCT (iOCT).adds to these efforts by multiplying the A-scan rate.

II. MATERIAL AND METHODS

A. System Design

The presented system is based on a swept-source OCT system, which is shown in Fig. 1. We used an Axsun (Billerica, USA) SS-1060 sweepable laser light source with a center wavelength of 1040nm and a bandwidth of 100nm. Its sweep rate is 100 kHz. The laser also provides a clock output that is a linear function of the wavenumber k of the output light.

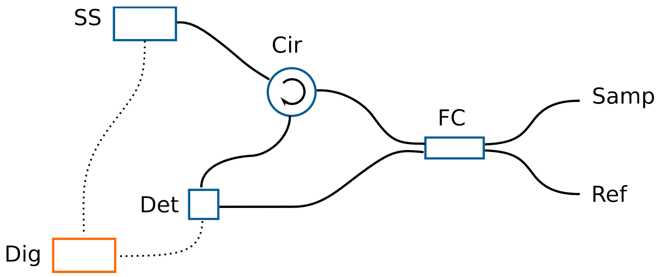

Fig. 1. Overview of our SS-OCT-System (SS: sweepable laser source, Cir: circulator, Det: detector, FC: fiber coupler, Samp: sample arm, Ref: reference arm and Dig: digitizer).

A New Focus (Santa Clara, USA) 1617 detector with an electronic bandwidth of 800 MHz was used in balance detection mode. The Signal was digitized at 500 MHz

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sampling rate by an Alazartech (Pointe-Claire, Canada) ATS 9350.

Light from the Axsun light source was sent through a circulator and a fiber coupler to the reference and the sample arms, where part of the light was reflected or backscattered into the fiber. The interference of sample and reference light was then measured by the balanced detector.

To measure several A-scans simultaneously, the sample arm of our system differs from that in traditional OCT systems.

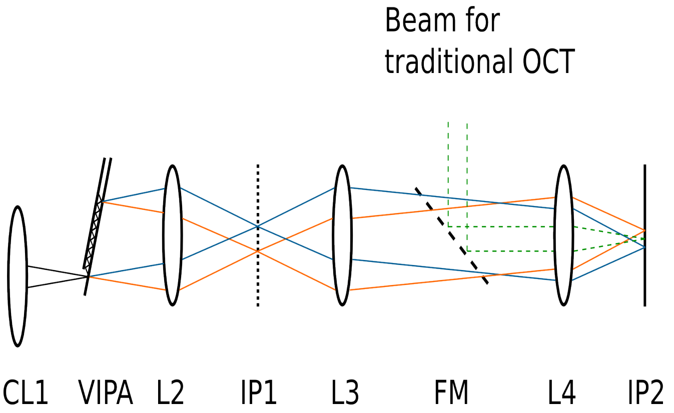

Fig. 2. Setup of the sample arm used for interleaved OCT (iOCT). A Cylindrical lens CL1 focuses the light on the virtually imaged phased array (VIPA). Lens L2 focuses the light into image plane IP1. The lenses L3 and L4 finally focus the light into in the image plane IP2 at the sample. For standard OCT imaging the VIPA can be bypassed via the flip mirror FM.

A virtually imaged phased array (VIPA) was added to the sample arm as shown in Fig. 2. The function of a VIPA is described in detail in [6]. In short, the VIPA is a multiband demultiplexer, which essentially consists of a glass slide with reflective coatings on both sides. One coating reflects 100% of the light and the other one is transmitting a small fraction of the light. Light coupled into this VIPA through an entrance window is reflected multiple times between the reflecting surfaces. With each reflection the optical path length increases by a certain amount. Constructive and destructive interference of the light leaving the VIPA through the partly reflecting surface selects certain wavelengths. As the optical path length depends on the propagation angle in the glass plate, different wavelengths are assigned to different output angles.

VIPAs were initially designed to be used as demultiplexers for light with a small bandwidth. If a VIPA is used with a convergent beam of a broad light source, multiple discrete wavelengths are assigned to the same angle, as shown in Fig. 3. We use this effect to distribute light of different wavelengths to different lateral positions.

The finesse of the VIPA and the linewidth of the light source thereby determine the number of resolvable lateral points. We used a glass VIPA custom built by Light Machinery (Nepean, Canada) with a finesse higher than 60, which in theory would allow us to resolve more than 60 lateral points. However in our case the linewidth of our light source is the limiting factor, allowing us to resolve only 9 lateral points.

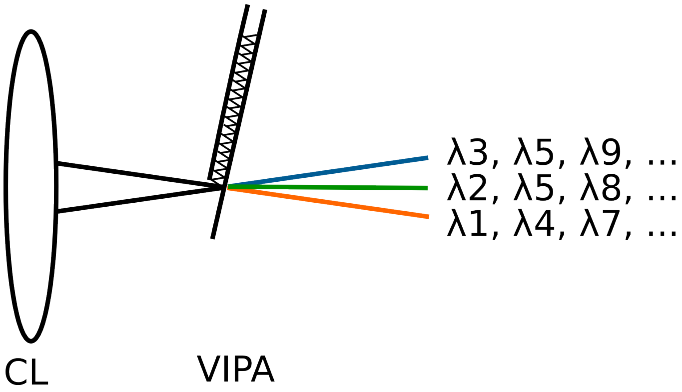

Fig. 3. Fig. 3. Assignment of different wavelengths coombs λ to different output angles by the VIPA. The cylindrical lens CL focusing the light onto VIPA's entrance slit.

As shown in Fig. 2 we added an additional intermediate image plane in the sample arm. This allowed us to limit the range of lateral points selected using a mask or slit. The collimated optical path between the Lenses L3 and L4 and a flip mirror allowed us to bypass the VIPA. By adding a galvo scanner this would allow us to compare both systems using the same sample without moving it.

B. Data processing

Before de-multiplexing and Fourier transform we subtracted a previously recorded dc-spectrum of the light source from the measured Interferogram. This corrected for noise and artifacts at depth in the later A-Scan. The k-clock signal provided by the Axsun light source was recorded with an Agilent (Santa Clara, USA) DSO-x 3052A oscilloscope. This data were used to linearize the interferogram in k during post processing. We furthermore used an algorithm to compensate for different dispersion in the sample and reference arms and applied a Hanning window to the interferogram to reduce side lobes in the later A-scan.

The iOCT interferogram contained the information of a B-scan of 9 different lateral points. Each wavelength set of the sweep was assigned to one of the 9 different lateral points. From the initial interferogram one interferogram with 245 different wavelengths was extracted for each lateral point. The log scaled Fourier transform of each interferogram resembles an A-scan. All 9 A-scans together comprise the B-scan measured during one sweep of the light source.

C. Experimental design

To show that we are able to assign different wavelengths to different lateral points, we took images of several sections of a 1951 USAF resolution test chart with our iOCT system.

Furthermore, we measured a mirror in different axial positions with our iOCT system in order to demonstrate our ability to resolve depth information.

III. RESULTS AND DISCUSSION

Our first images of test samples show the principle feasibility of lateral multiplexed SS-OCT imaging by using the VIPA. Fig. 4 shows the 9 adjacent A-scan imaging single bars of group 3, element 2 and group 3, element 6 of a 1951 USAF resolution test chart.

Even though the bars in the B-scans are clearly visible in both cases, some wavelengths were not assigned to the correct lateral position. This broadens the bar in lateral direction and causes artifacts in other imaging depths. This is mainly caused by the dispersion compensation algorithm we used, which was not properly adjusted to the iOCT processing.

Fig. 5 shows the same image of group 3, element 2 without dispersion compensation. The artifacts aren't present but the axial resolution is worse, resulting in a broader image of the bar in axial direction.

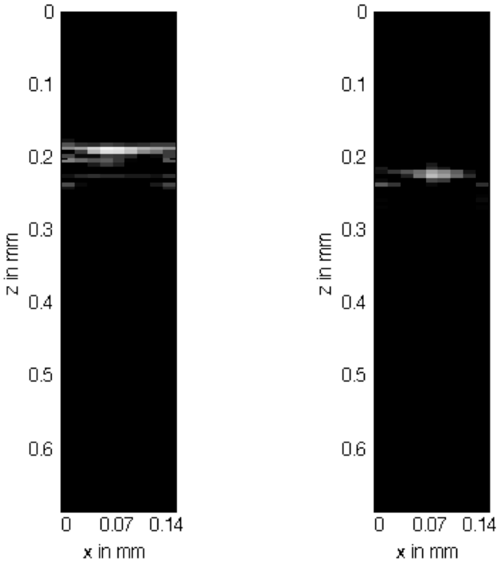

Fig. 4. Nine adjacent A-scans of a 1951 USAF resolution test chart group 3 element 2 single bar (left) and group 3 element 6 single bar (right). Some information in the interferogram was assigned to the wrong lateral point by the dispersion compensation algorithm, resulting in a broader signal.

Since the image contains information of only 9 lateral points, it is comparable with a B-scan of 9 points of a traditional system taken at an effective B-scan rate of 900 kHz.

From the iOCT image of a mirror, resolution and signal fall-off were determined (Fig. 6). The full width half maximum width of the peaks is about 10μm, which is about the resolution of a traditional OCT system with the same light source. Over the measurement range of 0.66 mm the signal falloff of intensity with imaging depth was negligible.

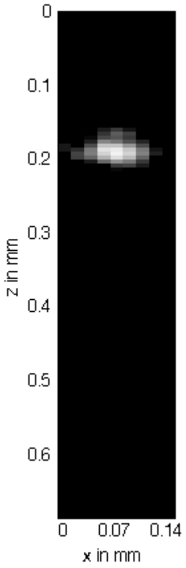

Fig. 5. B-scan of the 1951 USAF resolution test chart group 3 element 2 single bar without dispersion compensation.

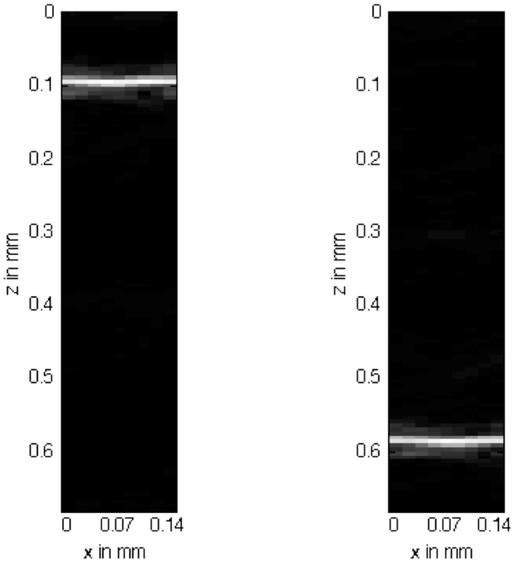

Fig. 6. B-scan of a mirror in different axial positions

IV. CONCLUSIONS

We developed a technique that allowed a 9 times increase of the imaging speed of an existing Fourier Domain OCT-Systems by adding a VIPA to the sample arm.

The number of resolvable points was limited by the linewidth of the light source and the desired imaging depth. With the rapid development of SS-OCT light sources like the VCSEL source, iOCT will allow researchers to transform excess imaging depth, which is inherently limited by the Rayleigh length, into additional lateral points.

Because iOCT does not require moving parts, it could replace existing fast scanning devices like galvo scanners and acousto-optic modulators in future OCT systems. This becomes especially interesting with the high imaging depth of single mode swept source lasers, which have a very small inherent linewidth. iOCT could also replace lateral scanning techniques in endoscopic probes.

Our setup furthermore suffered from a low sensitivity, probably caused by a loss of photons in the reflective layers of the VIPA and an incomplete dispersion compensation.

iOCT exchanges imaging depth, which is provided by future single mode light sources [3] by lateral imaging information. It extends the imaging speed beyond the limits of the swept-source laser and obviates the need for lateral scanning.

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